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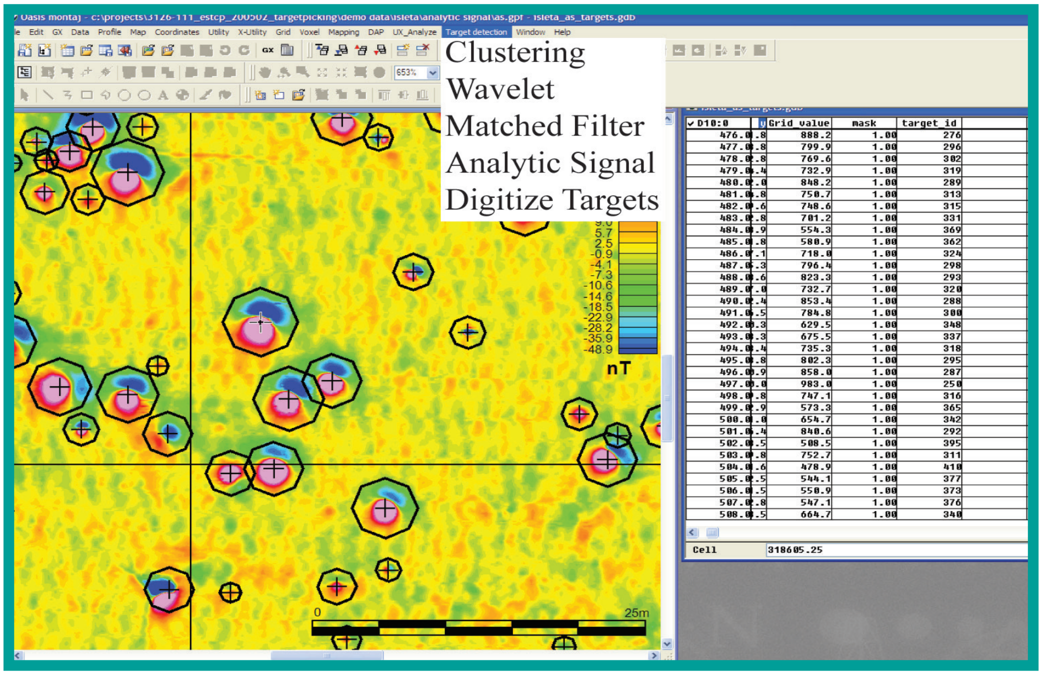

Target Picking Methods for Magnetic Data

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ACRONYMS AND ABBREVIATIONS

APG	Aberdeen Proving Ground
AS	analytic signal
AWD	Automated Wavelet Detection
BBR	Badlands Bombing Range
BT-4	Bombing Target 4
DoD	Department of Defense
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
GPO	geophysical proveout
GPS	Global Positioning System
GX	Geosoft Executables
IDL	Interactive Data Language
IPR	In-Progress Review
JPG	Jefferson Proving Ground
MF	matched filter
MFAP	Matched Filter AutoProcessor
MRA	Munitions Response Area
MTADS	Multisensor Towed Array Detection System
NAVEODTECHDIV	Naval Explosive Ordnance Disposal Technology Division
NRL	Naval Research Laboratory
Pd	probability of detection
Pfa	probability of false alarm
rBAR	background alarm rate
ROC	receiver operating characteristic
RTK	real-time kinematic
SERDP	Strategic Environmental Research and Development Program
SNR	signal-to-noise ratio
TAA	Technical Assistance Agreement
USACE	U.S. Army Corps of Engineers
UXO	unexploded ordnance
WAA	wide area assessment

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1.0 EXECUTIVE SUMMARY

Due to the large numbers (up to tens of thousands) of possible targets identified in nominal unexploded ordnance (UXO) surveys, efficient and reliable machine-aided target pickers should be used to identify targets for subsequent characterization. When selecting anomalies, the goal is to identify all anomalous features that may be caused by UXO, while minimizing operator time and eliminating operator bias. To facilitate advanced physics-based modeling, however, the target pickers should also be able to select data appropriate to the target, i.e., to outline or estimate the anomaly's spatial extent. The current approach to target selection is either manual identification or amplitude thresholding. The former is time-intensive, not clearly defined, and prone to operator bias. The latter is sensitive to noise and is prone to over- or under-picking unless judicious oversight is exercised. Neither approach provides measures for estimating the footprint of the anomaly. The impact to the Department of Defense (DoD) is obvious. Systematic, fast, and robust target pickers can save money and produce a defensible target list compared to the current methods.

This project evaluated four automatic target pickers as well as the manual method and transitioned them to the user community via Oasis montaj™ by building custom Geosoft Executables (GX). Oasis montaj™ is a geophysical data processing and visualization package developed and marketed by Geosoft Incorporated. The four automatic target pickers were: (1) a wavelet-based detection algorithm, (2) clustering positive and negative peaks, (3) a dipole-based matched filter (MF), and (4) analytic signal (AS).

The demonstration was broken up into two phases. The first phase used a 60-dipole synthetic dataset to explore the parameter space and optimize the algorithms for the four automatic target pickers. The result of Phase 1 was a set of starting parameters that was used in Phase 2. The second phase applied the target pickers to seven magnetic datasets using the parameters output from Phase 1 as a starting point. The seven datasets possessed different signal and noise characteristics and anomaly densities. Three datasets provided from the U.S. Army Corps of Engineers (USACE)─a helicopter-towed wide area assessment (WAA) dataset, a vehicle-towed transect WAA dataset, and vehicle-towed Multisensor Towed Array Detection System (MTADS) datasets from the Aberdeen Proving Ground (APG) standardized test site and Target S1 at Isleta Pueblo in New Mexico─were used for the evaluation. Because each dataset has its own unique data characteristics, the starting parameters were adjusted iteratively to achieve the best performance. The knowledge gained from Phase 1 was used to guide these adjustments.

The primary performance objectives were to detect >90% of the ground truthed targets for production surveys (>80% for WAA) in <¼ the time needed for the manual method. The detection objective was met by some of the automatic pickers on some of the datasets. The time objective was met by all the automatic methods for all the datasets.

A stated objective in the DoD's Report to Congress in 2001 was to develop standards and protocols for navigation, geolocation, data acquisition and processing, and performance of UXO technologies. These include standard software and visualization tools to provide regulatory and public visibility to and understanding of the analysis and decision process made in response activities [1, 2].

The detection rates for the automatic methods were heavily dependent on the data quality, noise characteristics, and target density. In general, the amount of geology and background noise affected the performance of the automatic methods the most. All the methods require a threshold to be set that is based on the noise characteristics of the data. Because of this, automatic methods will pick anomalies with signal amplitudes above the threshold that are caused by noisy data or geology and not pick the valid anomalies located in the quieter areas that are below the threshold. Datasets that contained a consistent background noise level across the area, as seen in the Isleta dataset, performed well, with all methods exceeding the 90% detection rate. Conversely, the WAA helicopter dataset contained a variety of noise levels due to geology, which caused 50% detection rates for all automatic methods. The manual method has an advantage in these areas because the analyst can set a lower picking threshold and dynamically filter out the picks that are obviously due to geology. This ability may also be a drawback because it may introduce operator error or operator bias. The other main drawback to the manual method is the time required to pick the anomalies.

Of the automatic methods, the AS and wavelet method gave the best results overall, but each method had its own strengths and weaknesses, and the best method was very data-dependent. A general observation for all the automatic pickers is that they should not be run blindly. The analyst should carefully choose their parameters and analyze the results. The process of iteratively changing parameters and visual review of the results was essential in selecting the best parameters.

Implementation of the automatic picking methods used in this demonstration should considerably reduce the time and thus cost required to pick anomalies when compared to the manual method. The amount of cost savings will depend on the data. In areas with isolated anomalies and low background noise or geology, the cost savings will be maximized because the automatic pickers are able to detect over 90% of the anomalies in a fraction of the time compared to the manual method. As the geologic noise increases or data quality decreases, the cost savings will diminish because the missed anomalies will need to be filled in using the time-consuming manual method, but cost savings still should be significant.

The stakeholders and end users of this data processing and analysis technology include private contractors who conduct geophysical investigations in support of UXO cleanup programs and governmental employees who provide technical oversight. This demonstration showed the data products associated with this analysis approach and the inherent transparency of the target picking process. This basic information will help to improve the results of future geophysical investigations conducted by others. The market for this type of guidance document includes all practicing geophysical service firms currently working in the UXO industry.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENTS AND APPLICATION

The user community would benefit from an algorithm that accurately identifies and locates magnetic anomalies using quantifiable decision criteria and limited user interactions. The underlying aim is to reduce analysts' bias because it is not predictable, consistent, or correctable. This project made and compared anomaly declarations for each dataset chosen using the following five approaches: (1) a wavelet-based detection algorithm, (2) clustering positive and negative peaks, (3) a dipole-based MF, (4) AS, and (5) manual selection. Each approach is described below. We also evaluated how each method can be used to identify the anomaly's spatial extent.

Wavelet-Based Algorithm. Billings and Herrmann (2003) developed a magnetic target picking method called the Automated Wavelet Detection (AWD) algorithm [3]. In that method, individual peaks in the magnetic data are followed across multiple scales, with the decay in peak amplitude related to the depth to the source. Nearby positive and negative peaks in the image are only joined together if they satisfy two conditions: (1) the peaks must have comparable depth estimates and (2) the peaks must move towards each other as the wavelet scale becomes finer. In this way, one can avoid incorrectly joining the peaks from nearby dipoles. In the last stage of the algorithm, the amplitudes of the peaks and their relative position are used to provide an initial estimate of the dipole parameters, including a good initial estimate of the size of the region to invert about each anomaly.

Rule-Based Clusters. Rule-based clustering approaches threshold the magnetic data to identify positive and negative groups and then associate positive and negative clusters using codified rules to form anomalies. The degree to which they work depends on the noise and signal characteristics of the data and on details of the rules that associate negative and positive clusters. We have identified two rule-based schemes that have been developed and codified under previous research efforts.

The first is an automatic target picker developed during Strategic Environmental Research and Development Program (SERDP) CU-1092 by Blackhawk Geometrics, Inc. [4]. In this version, thresholds for positive and negative data are set by the user. The negative and positive clusters are then identified, and each negative anomaly is associated with the most plausible nearby positive anomaly. The most plausible positive anomaly is determined by a formula that reflects the distance, magnitude of both anomalies, and degree of consistency with the local magnetic declination. Isolated negative anomalies are discarded as noise. As detailed in the CU-1092 project report, there are issues with regard to matching positive and negative lobes in cases where the anomalies are tightly packed and/or overlapping. There are also issues with regard to the picker dividing one anomaly into two if there are minor amplitude sags (due perhaps to inter-sensor difference, heading errors, or gridding).

The second rule-based scheme was developed and codified by AETC Incorporated under funding from Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV) in 1995. Similar to the code developed under CU-1092, it asks the user to identify thresholds, uses the

thresholds to create positive and negative clusters, and then associates the clusters in favor of combinations with the least distance between centers.

Dipole-Based MF. AETC developed, under Environmental Security Technology Certification Program (ESTCP) Project 199918, a Matched Filter AutoProcessor (MFAP) for magnetometer data [5, 6]. This algorithm implements a MF based on a magnetic dipole signal. After the magnetometer data is interpolated onto a regular x-y grid, it is automatically convolved with a magnetic dipole signal model for a target accompanied by a search over the unknown parameters in the signal model (target orientation, moment, etc.) to maximize the filter output. The output of the MF routine is a surface (grid) that peaks directly over the target location. Because of this, it can be thresholded to identify targets. The MFAP approach was developed in the Interactive Data Language (IDL) (Research Systems, Inc.) but has subsequently been integrated with OASIS montaj^{TM}.

Once the MF output is calculated, the user must identify individual anomalies by picking peaks above the background noise. The spatial extent of each anomaly can be estimated by using the initial fitted parameters output during the match fitting process to calculate a boundary that contains a certain percentage of the total energy.

Analytic Signal. The AS is a positive quantity derived from magnetometer data. It can easily be thresholded for target detection and is commonly used by commercial practitioners. The AS is the square root of the sum of the gradients in three directions:

$$AS = \sqrt{\left|\frac{\partial B}{\partial x}\right|^2 + \left|\frac{\partial B}{\partial y}\right|^2 + \left|\frac{\partial B}{\partial z}\right|^2} \ ,$$

where the z-gradient is formed from the data in the (x,y) plane by upward continuation in the Fourier domain:

$$\frac{\partial B(k)}{\partial z} = kB(k), \quad k = 2\pi / \lambda \ .$$

Once the AS is calculated, the user must identify individual anomalies by picking peaks above the background noise. The spatial extent of each anomaly can be estimated by examining the nature of the anomaly in terms of its inflection points or change in total energy.

Manual Anomaly Selection. As a baseline measure, we manually identified individual anomalies and estimated the spatial footprint of each anomaly using an experienced analyst from NAEVA Geophysics. The analyst was asked to select all anomalies above the noise level of the given dataset. The analyst decided on the noise threshold and properly documented the rationale behind the threshold. The analyst was free to use the preferred analysis environment.

2.2 PROCESS DESCRIPTION

This demonstration used target picking algorithms that have been prototyped and tested during previous research programs. Three of the algorithms (AWD, MF, and clustering) have been seamlessly integrated into Oasis montaj^{TM} under this project. The AS algorithm is included with appropriately licensed versions of Oasis montaj^{TM}. All processing and analysis performed in this demonstration was done in the Oasis montaj^{TM} environment.

The demonstration was broken up into two phases. The first phase used a 60-dipole synthetic dataset (Figure 1) to explore the parameter space and optimize the algorithms for the four automatic target pickers. The synthetic dataset consisted of six target sizes (20 mm, 40 mm, 60 mm, 81 mm, 105 mm, and 155 mm) randomly placed at depths up to 11 times the target diameter. The result of Phase 1 was a set of starting parameters that was used in Phase 2.

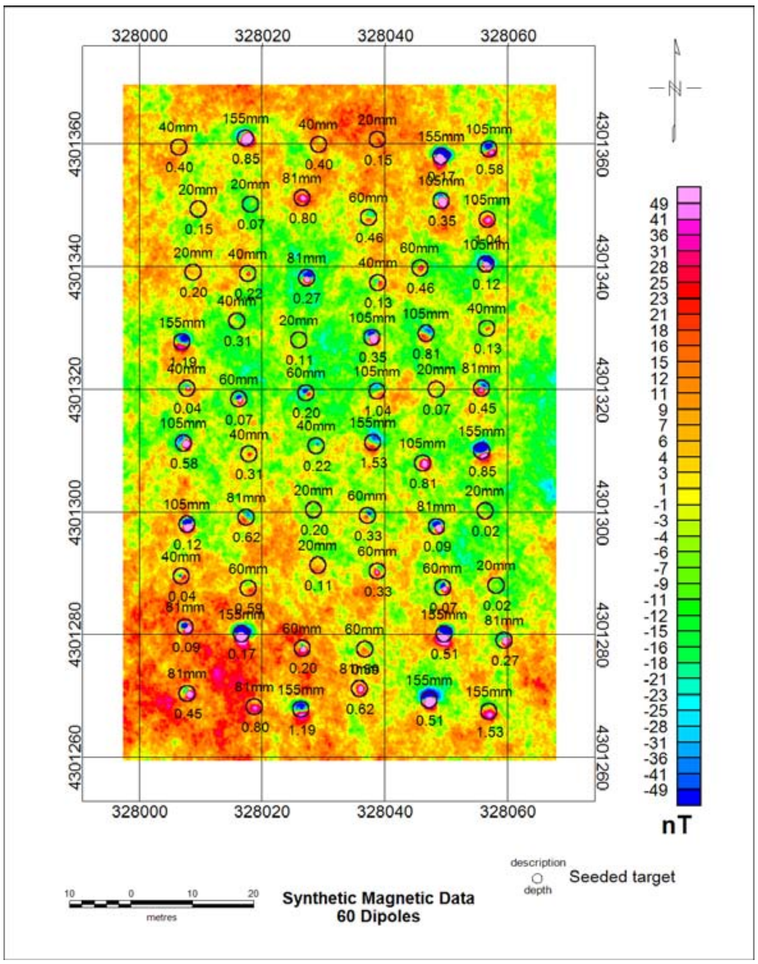

Figure 1. Synthetic Magnetic Dataset with 60 Targets.

Phase 2 applied the target pickers to the seven magnetic datasets used in this demonstration using the parameters output from Phase 1. Because each dataset has its own unique data characteristics, the starting parameters were adjusted iteratively using knowledge gained from Phase 1 to achieve the best performance. The process involved running the algorithms on the datasets (for

large datasets a small portion of the data was used) and changing the parameters based on a visual review of the results. Several iterations were run until the optimal parameters were chosen. The visual review involved looking at the types of anomalies that were visible in the data and changing the parameters to select the desired anomalies. We also looked at all the automatic picks and determined if they were valid or in the noise levels of the dataset and adjusted the threshold accordingly.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

The AWD algorithm has been successfully applied at the University of British Columbia as part of the work funded by Engineer Research and Development Center (ERDC) (DAAD19-00-0-0120). The algorithm was demonstrated on three datasets with different characteristics [3]. In each case, the method rapidly located the majority of dipole anomalies and produced accurate estimates of the dipole parameters.

The two rule-based clustering algorithms used as a basis for the clustering algorithm developed for this project were previously tested during their development as part of the work funded by SERDP (CU-1092) and NAVEODTECHDIV. The AETC clustering algorithm was also tested on data collected at the Badlands Bombing Range (BBR) on the Pine Ridge Reservation in South Dakota and at Twentynine Palms, California [7]. The results of this test showed the automatic processor detecting about 90-100% of the objects present with the most significant detection factor being target density. In low density regions, almost 100% of the objects were found, whereas in high density areas the detection rate fell to 90%. It was estimated that the automatic processor could analyze about four times more data than the manual processor in the same amount of time.

Previous testing of the MF algorithm included MTADS magnetometer survey data over several sites (Twentynine Palms, Blossom Point, and Buckley Field). The algorithm was also tested on the three 1-hectacre areas of the 2000 Advanced UXO Detection/Discrimination Technology Demonstration at Jefferson Proving Ground (JPG). The MF did a good job at isolating potential targets at JPG [5]. The filter output peaked over the targets, which helped reduce the ambiguity of the exact target location. The low probability of detection (Pd) (80%) was caused by data gaps and the difficulty in finding 20 mm using magnetometer data with a sensor spacing of 25 cm.

The AS is included with appropriately licensed versions of Oasis montaj™ and is commonly used by commercial analysts. As such, it has undergone internal testing of the algorithm at Geosoft and extensive practical testing by the user community.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

This demonstration used already collected survey data to test four automatic target pickers and transitioned the algorithms to the user community through Oasis montaj™. The main advantage of using automatic methods to pick anomalies is the time it can save. On large remediation projects with thousands of anomalies, the manual method is very slow. Another aspect of the manual method is its subjective nature. Different data analysts may have different criteria on what is and is not an anomaly. It may be based on signal level and signal shape, which is

directly affected by the way the data is displayed. The target density of the data may also affect the analyst's decision. In areas of low density, the analyst may be prone to pick smaller and weaker anomalies for the sake of picking something. Conversely, in high-density areas the analyst may set his threshold higher. Based on these two difficulties, automatic target pickers are desirable because they would be limited only by the speed of the computer and can be set to select targets using fixed criteria.

Previous testing of the automatic pickers has shown limitations to the technology. The clustering and AS algorithms may have trouble with low signal-to-noise signatures and high background noise. In these areas, a low threshold must be chosen to pick the weaker anomalies, but by lowering the threshold, the automatic pickers will pick many anomalies that are caused by noise in the data.

The MF algorithm cannot filter a point if there are any missing data in the filter box. Thus, the edges of a survey site cannot be filtered as well as any interior regions that are missing data. Therefore, a small data gap of 0.5x5 m becomes an unfilterable region of 3.5x8 m if a 3 m filter box is used. For this reason the match filter algorithm cannot be used on the WAA vehicular transect data because the width of the transect is only 1.75 m.

The AS and AWD algorithms map and interpolate the magnetic data to a regular x-y grid and apply their respective filters to the grid. For normal surveys, this would not be an issue but applying them to transect data may require some optimization. Because transects can cover large areas in a single sortie, the resultant grid can get very large given that the grid produced is based on the minimum and maximum XY values. If the transect lines are relatively straight along one geographic heading, the data can be rotated prior to creating the grid such that the lines are oriented along either the grid rows or columns.

The AS and MF algorithms output an anomalous surface and not the locations of the anomalies. Therefore, a second program must be run to detect the peaks in the surfaces. Thus, the success of these methods is partially dependent on the peak picking program.

The clustering and AWD algorithms have several parameters that need to be set. The option to change many of the parameters allows the user the flexibility to tune the algorithms to the individual data characteristics. However, this flexibility adds to the complexity and setup time to ensure that the proper parameters are picked to achieve optimum performance of the algorithms.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Table 1 and Table 2 outline the performance objectives for the production and WAA surveys, respectively. The values of the quantitative performance objectives for the production surveys were chosen to measure how practical the methods are for use in the "real" world. The picks by the different methods were compared to the ground truth for the production surveys by calculating the Pd defined as (number of detections picked by an automatic picker that are coincident to a ground truth object / number of ground truthed objects). The background alarm rate (rBAR) defined as (number of detections picked by automatic picker not caused by ground truthed object / arbitrary number (in order to conceal the absolute number of truth items) was calculated only for the APG dataset. This was because none of the other datasets contained complete ground truth so the additional picks may or may not have been caused by a valid object. Because the calculation used an arbitrary number, the actual performance metric is meaningless but useful information is gained by comparing the number among the different target picking methods. The manual method was used as the baseline to judge the efficiency of the different methods. Our goal is for the processing time (time required to run automatic picker / time required to manually pick the anomalies) to be less than 0.25 hr. This would allow plenty of time to manually alter the automatic picks to achieve the best possible performance and still complete the analysis in less time than in using only the manual method.

We compared the fitted parameters using results from the automatic methods and the manual method to ground truth information for 80 targets at APG. The XY location and a boundary file that estimates the anomaly's spatial extent were used as inputs to advanced physics-based inversion routines that output target features such as XY location, depth, and size. The detection location accuracy is defined as the horizontal distance between the picked location that is output directly from the target picking algorithms and the ground truth location. The characterization location accuracy is the horizontal distance between the XY position output from the inversion routines and the ground truth location. Therefore, assuming good data quality the characterization location should be more accurate than the detection location. The characterization size accuracy is defined as (the absolute difference between the fitted target diameter and the ground truth diameter)/(ground truth diameter). The location, depth, and size metrics were set to values that would enable the dig teams to easily find the target.

The WAA surveys have similar performance criteria as the production surveys, but because of differing objectives the expected performance will be different. The general objective of the WAA surveys is to delineate munitions response sites, support regulatory disposition of non-munitions response sites and provide reliable data to support risk analysis and remedial cost estimation. The Pd metric is lower because of the different objectives. To achieve these goals, airborne magnetometer data and vehicle-based magnetic transect data were collected. These datasets have much lower data densities, which results in the location metrics being higher than for production surveys. Also, ground truth data was not available for the WAA data sets so the Pd and probability of false alarm (Pfa) were calculated using the manual picks as the baseline.

Table 1. Performance Objectives for Production Surveys.

Primary Performance Criteria	Description	Expected Performance (metric)	Actual Performance Objective Met?
Qualitative Performance Criteria			
Ease of use	Processing flow and the anticipated skill level required	Limited training required for users experienced in Oasis montaj^{TM}	Yes
Robustness	Analysts' experience related to bugs and program deficiencies	Analysis not hindered by bugs or deficiencies	Yes
Quantitative Performance Criteria			
Pd (ground truth)	(number of detections picked by automatic picker that are coincident to ground truth target)/(number of ground truth targets)	>0.9	Yes/No
rBAR (APG only)	(number of detections picked by automatic picker but not matching ground truth object)/ (arbitrary number)	NA	NA
Setup time	Time required to setup optimum parameters	<4 hours	Yes/No
Processing time	(Time required to run automatic picker)/(time for commercial expert to pick anomalies)	<0.25 hr.	Yes
Detection location accuracy	The horizontal distance between picked and ground truth location	90% <0.5 m	Yes/No
Characterization size accuracy (APG only)	(The absolute difference between the fitted target diameter and the ground truth diameter)/(ground truth diameter)	90% <0.3 m	No
Characterization location accuracy (APG only)	The horizontal distance between the fitted XY position and ground truth location	90% <0.3 m	Yes
Characterization depth accuracy (APG only)	The difference between the fitted depth and ground truth depth	90 % <0.3 m	Yes

Table 2. Performance Objectives for WAA Surveys.

Primary Performance Criteria	Description	Expected Performance (metric)	Actual Performance Objective Met?
Qualitative Performance Criteria			
Ease of use	Processing flow and the anticipated skill level required	Limited training required for users experienced in Oasis montaj™	Yes
Robustness	Analysts' experience related to bugs and program deficiencies	Analysis not hindered by bugs or deficiencies	Yes
Quantitative Performance Criteria			
Pd (manual picks)	(number of detections picked by automatic picker that are coincident to manual pick)/(number of manual picks)	>0.8	No
Pfa	(number of detections picked by automatic picker but not matching manual pick)/(number of manual picks)	<0.25	Yes/No
Setup time	Time required to setup optimum parameters	<4 hours	Yes/No
Processing time	(Time required to run automatic picker)/(time for commercial expert to pick anomalies)	<0.25 hr.	Yes
Detection location accuracy	The horizontal distance between picked and manual pick location	90% <1.5 m	Yes

3.2 SELECTING TEST SITES

This demonstration was performed in the Cary, North Carolina, office of SAIC (formerly AETC) on data that was previously collected on government ranges for other purposes. There are thus no regulatory, health, or safety issues affecting this demonstration.

The USACE was asked to provide examples of datasets that are representative of that acquired by their contractors and that support our requirements. Our criteria for the demonstration data sets were the following: a) a range of data density and target sizes, and a variety of target types were needed to explore the capabilities and performance of the four automatic pickers; b) a range of signal-to-noise ratio (SNR) from marginal to excellent in order to derive conclusions that can be extrapolated for future use; c) data was collected from different platforms, including vehicular, man portable, and airborne; d) datasets that are of both standard contractor and research quality in terms of sensor noise, lag, etc.; e) data sets containing at least 100, but ideally no more than 500, anomalies; f) survey objective (WAA or production); and g) available ground truth information. Complete ground truth information was desirable for all datasets but not absolutely necessary. When available, we focused our analysis on comparing the anomaly picks to the ground truth information. If this information was not available, we used the manual picks as the baseline for comparison to the automatic picks. Accurate ground truth information (location, burial depth, size, and description) was needed for 50-100 targets in order to compare the location accuracy and the extracted spatial footprint of the anomaly for the different picking algorithms.

Table 3 summarizes how well the datasets fit our demonstration criteria.

Table 3. Criteria and Datasets.

Dataset/ Criteria	Naval Research Laboratory (NRL) MTADS APG June 2004	USACE JPG	USACE Geophysical Proveout (GPO) Data	WAA Pueblo BT4 Ground Transects	WAA Pueblo BT4 Airborne	Isleta Vehicle	Seaside
Target sizes	20 mm 40 mm 57 mm 60 mm 81 mm 2.75 in 105 mm 155 mm bdu28 blu26 M42 MK118	OE scrap 4.5 in head, mortar burster	MKIIgrenade MKII17#bomb MKI 25#bomb range clutter	M38 MK15 GP Bomb	M38 MK15 GP Bomb	60 mm 81 mm 2.75 in 105 mm BDU33 MK76 M38 GP bomb	37 mm, 60 mm, 3.5 in M29, Grenade fuze, Non OE scrap
Target density	low-high	low-high	low-med	low-med	low-med	low-med	low-high
Platform	vehicle	handheld	handheld	vehicle	airborne	vehicle	handheld
Data quality	high [research]	low [standard]	med [standard]	high [research]	high [research]	high [research]	med [standard]
SNR	low-high	low-high	low-high	low-high	low-high	low-high	low-high
Geologic noise	low-med	low	low-high	low-med	med-high	low-med	low-med
Number of ground truthed anomalies	All, but not released to public	253	33	2	0	150	481
Survey objective	production	production	production	WAA	WAA	production	production
Picking methods	AWD, AS, MF, clustering, manual	AWD, AS, MF, clustering, manual	AWD, AS, MF, clustering, manual	AWD, AS, clustering, manual	AWD, AS, MF, clustering, manual	AWD, AS, MF, clustering, manual	AWD, AS, MF, clustering, manual

Three of the datasets were acquired using the vehicle-towed MTADS by NRL and AETC. MTADS hardware consists of a low magnetic signature vehicle that is used to tow an array of eight magnetic sensors that are spaced .25 m apart. The sensor positions were determined using real-time kinematic (RTK) Global Positioning System (GPS) receivers. The three data sets were collected at 1) open field grid of the APG standardized test site in June 2004; 2) Target S1 on the Pueblo of Isleta near Albuquerque, New Mexico, in February 2003; and 3) area near Bombing Target 4 (BT-4) at Pueblo PBR in Colorado in September 2005.

Another data set was collected by Sky Research and AETC using the airborne MTADS system. The system hardware includes an array of seven magnetometers spaced 1.5 m apart in a 9 m boom mounted on a Bell 206L helicopter. The sensor positions were determined using RTK GPS

technology. The data collected was in the same vicinity as the above-mentioned vehicle-towed MTADS data near BT-4 at Pueblo PBR.

USACE contractors acquired the remaining three datasets. American Technologies Incorporated acquired data on a removal action over a 300-acre area at JPG. The data were collected using the handheld Geometric G-858G vertical gradiometer system in fiducial positioning mode. Two magnetometers were vertically separated by 2 feet and data were collected using a lane spacing of 2.5 feet. NAEVA Geophysics collected magnetic data over a GPO. (The USACE has requested that the site specifics be confidential.) The data were collected using a single handheld magnetometer with a line spacing of 2 feet and positioned using RTK GPS. The last dataset was collected by Parsons over the Seaside area at the Former Fort Ord. The data were collected using a handheld array of four magnetometers spread cross line at 2-foot intervals and positioned using RTK GPS.

3.3 TEST SITE HISTORY/CHARACTERISTICS

The area of the Aberdeen Test Site is adjacent to the Trench Warfare facility at the APG. The APG Standardized Test Site is located within a secured range area of the APG. The Aberdeen area of APG is located approximately 30 miles northeast of Baltimore at the northern end of the Chesapeake Bay. The Standardized Test Site encompasses 17 acres of upland and lowland flats, woods, and wetlands. The test site is divided into calibration lanes, blind grid test grid, open field, mogul, and wooded areas. Additional details regarding the layout of the APG Standardized Test Site can be found at http://aec.army.mil/usaec/technology/uxo03c01.html.

The total area of the former Pueblo Precision Bombing and Pattern Gunnery Range #2 is 67,769 acres, and it is located approximately 20 miles south of La Junta, Colorado, in Otero County. The closest community is La Junta, a rural town with a population of 7,637. The Munitions Response Area (MRA) was used by local populations for cattle grazing until the War Department assumed control of the lands to construct the Pueblo Precision Bombing and Pattern Gunnery Range #2 (1942 to 1946).

The Pueblo of Isleta is located in north-central New Mexico, approximately 10 miles south of Albuquerque. The reservation is bordered on the north by the Sandia Military Reservation, which includes Kirtland Air Force Base, the Manzano Mountains on the east, and the Rio Puerco and Laguna Pueblo Reservation on the west. The area that contains target S1 comprises approximately 7,000 acres that were leased from the tribe in the 1950s for use as a target bombing range for aircraft from Kirtland. Documentation in Bureau of Indian Affairs files indicates that this area was used as a practice bombing range from 1956 to 1961 to determine the performance of fast aircraft during bombing runs. In the 1960s, Kirtland collected and piled visible ordnance debris for removal. Up to 2 tons of practice bombs and ordnance waste per acre were removed but no explosive ordnance was found.

JPG, a 55,265-acre facility was established in December 1940, fired its first round 5 months later, and operated until 1995. JPG’s primary mission was to perform production and post-production tests of conventional ammunition components and other ordnance items and to conduct tests of propellant ammunition/weapons systems and components for the U.S. Army. JPG is located in southeastern Indiana, approximately 8 miles north of the Indiana-Kentucky

border and about 5 miles north of Madison, Indiana. Lands surrounding JPG are predominantly farmland and woodlands, with some small towns and rural residential land use nearby.

The former Fort Ord is located 80 miles south of San Francisco and occupies approximately 28,000 acres adjacent to Monterey Bay and the cities of Marina, Seaside, Sand City, Del Rey Oaks, and Monterey. Fort Ord became a training installation in 1917 and was used to train Army infantry, cavalry, and field artillery divisions for WWI, WWII, the Korean War, the Vietnam War, and Desert Storm.

3.4 PHYSICAL SETUP AND OPERATION

This data analysis demonstration utilized data previously collected on government ranges for other purposes. As such, no site preparation or installations were required for this demonstration. Key chronological dates with regard to the overall program are listed in Table 4.

Table 4. Target Picking Demonstration Schedule.

Date	Action
November 2006	Receive approval for Demonstration Plan
December 1-15, 2006	Phase 1 testing using a 60-dipole synthetic dataset
December 15, 2006 – January 15, 2007	Applied AS and MF algorithms to all demonstration datasets
January 15 – February 1, 2007	Applied clustering algorithm to 3 of 7 demonstration datasets
January 15 – February 15, 2007	Applied AWD algorithm to all demonstration datasets
May 2007	Presented preliminary results at In-Progress Review (IPR)
July 2007	Received new Technical Assistance Agreement (TAA) with Geosoft, fixed memory-related bug in clustering algorithm, and analyzed four remaining datasets
March 2008	Received performance results from IDA for APG dataset
March 2008	Submitted ESTCP Draft Final Report

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

The results of the first phase of the demonstration using the 60-dipole synthetic dataset are summarized in Figure 2, which shows that none of the automatic target pickers detected all the targets. The AS and the wavelet produced the best results followed by the clustering algorithm and finally the MF.

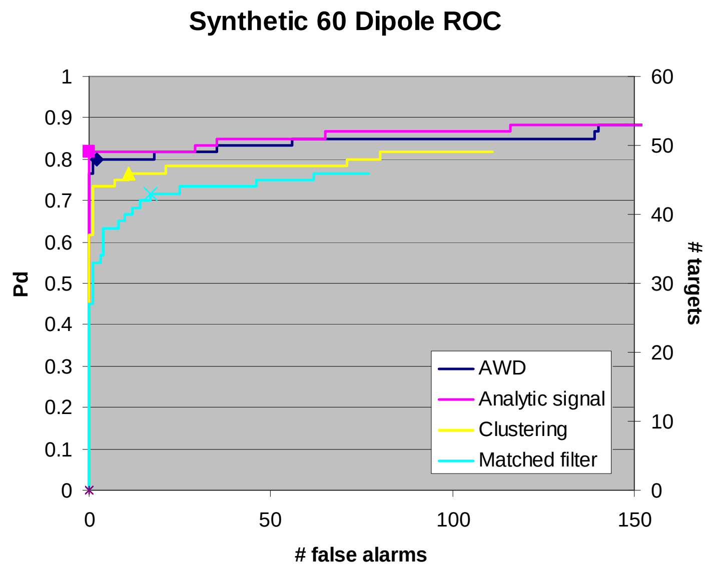

Figure 2. Receiver Operating Characteristic (ROC) Curve of the Different Target Pickers for the Synthetic 60-Dipole Data. (The symbols along each line represent the analyst's threshold value.)

Detection and location accuracy and target picking time for the live site datasets analyzed in Phase 2 are reported in Table 5 to Table 7 and Figure 3 to Figure 6. All the production survey datasets compared the declarations made by the different methods to the available ground truth to calculate the Pd. All the WAA survey data sets compared the declarations made by the automatic pickers to the picks made by the commercial expert to calculate the Pd and Pfa because ground truth did not exist. The Pds for the production survey datasets ranged from .15 to .99. The variety can be mainly attributed to the differences in data and available ground truth. The Isleta demonstration showed very good results with Pds for all methods above .90, whereas the Seaside demonstration had low Pds because the ground truth contained many objects with a weight less than a 20 mm projectile. Over 90% of the missed targets at Seaside were attributed to these small items. As part of our analysis, we plotted the ground truth sorted by decreasing AS amplitude versus the number of targets detected by each picking method (Figure 3 to Figure 6). This would ideally give a straight line along the diagonal if all the ground truth were detected. By sorting according to signal strength, we are able to visually see if there are trends in the types of targets missed for the different datasets. It also gives a visual sanity check of the thresholds selected for the different methods.

The actual time it took to set up the optimum parameters and run the automatic target pickers was recorded for each algorithm and dataset. We also measured the setup time and processing time separately because the setup time will be major component of the total time for the relatively small datasets we used in this demonstration.

Table 5. Detection and Location Accuracy—USACE GPO, Isleta, and Seaside.

Parameter / Method	USACE GPO			Isleta			Seaside		
	Total # picks	Pd	% within .5 m	Total # picks	Pd	% within .5 m	Total # picks	Pd	% within .5 m
Ground truth	28			145			412		
Manual	36	0.89	88	1,466	0.98	80	205	0.33	84
Clustering	27	0.57	63	758	0.98	84	160	0.25	69
Wavelet	39	0.75	81	1,454	0.99	86	616	0.60	87
Matched filter	14	0.36	70	472	0.90	86	123	0.15	85
Analytic signal	50	0.79	95	1,278	0.98	82	346	0.53	83

Table 3. Detection and Location Accuracy—JPG and APG.

Parameter / Method	JPG			APG			
	Total # picks	Pd	% within .5 m	Total # picks	Pd	rBAR	Average miss Distance (m)
Ground truth	190			NA			
Manual	532	0.95	84	707	0.9	0.58	.204
Clustering	359	0.92	86	444	0.8	0.335	.196
Wavelet	491	0.95	89	743	0.85	0.615	.212
Matched filter	309	0.72	87	206	0.7	0.105	.171
Analytic signal	393	0.92	82	620	0.9	0.495	.225

Table 4. Detection and Location Accuracy—WAA Surveys.

	WAA Pueblo Airborne				WAA Pueblo Transects			
Parameter / Method	Total # picks	Pd	Pfa	% within 1.5 m	Total # picks	Pd	Pfa	% within .5 m
Manual	383				887			
Clustering	387	0.55	0.46	92	454	0.49	0.02	95
Wavelet	547	0.53	0.90	92	1,049	0.76	0.42	92
Matched filter	323	0.50	0.34	94	NA	NA	NA	NA
Analytic signal	397	0.53	0.50	99	505	0.55	0.02	100

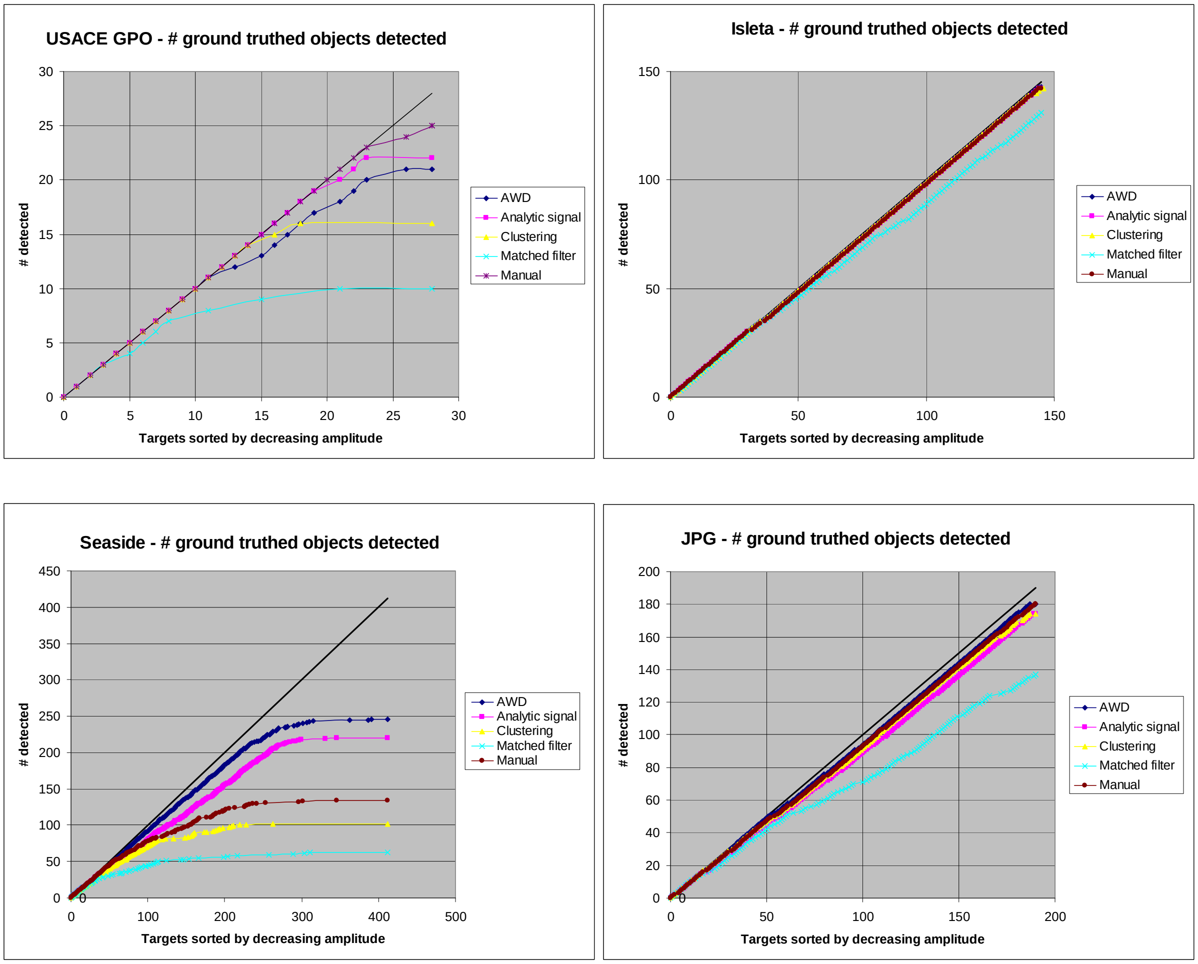

Figure 3. Graphs Showing the Number of Ground Truth Objects Detected by Each Method as a Function of Signal Amplitude (USACE GPO [top left], Isleta [top right], Seaside [bottom left], and JPG [bottom right])**.**

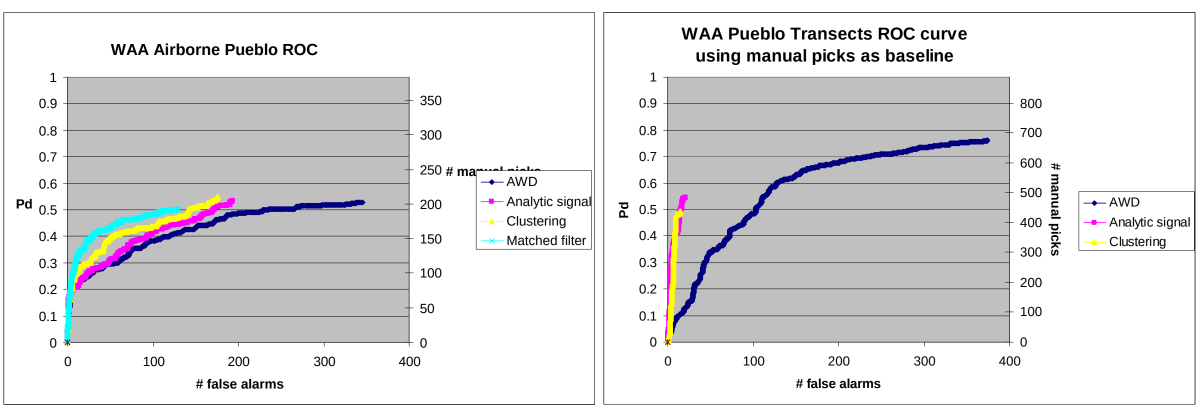

Figure 4. Graphs Showing Pd Versus the Number of False Alarms (automatic picks not matching manual picks) (Pueblo Airborne [left] and Pueblo Transects [right])**.**

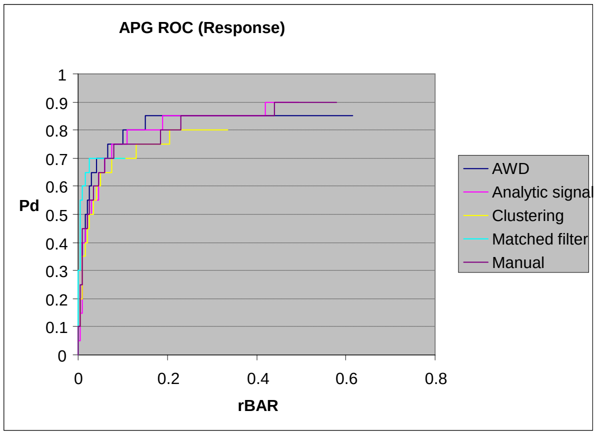

Figure 5. Receiver Operating Curve Showing the Number of Ground Truth Objects Detected by Each Method Versus Background Alarm Rate (APG)**.**

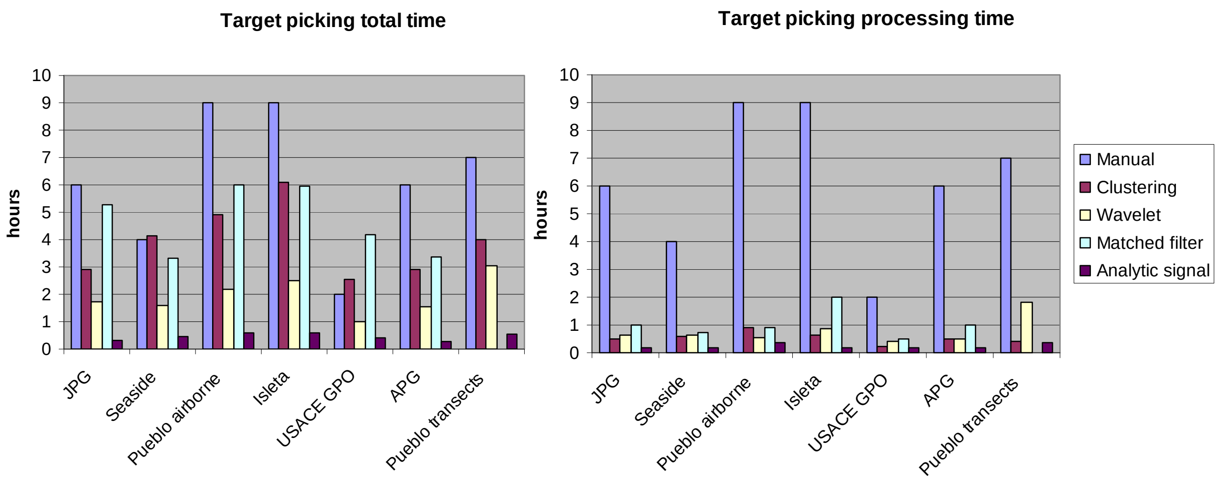

Figure 6. Graph Showing the Total Time (includes setup time) **and Processing Time to Analyze the Data Sets for Each Target Picking Method.**

4.2 PERFORMANCE CRITERIA

This demonstration resulted in 32 sets of scores. A set of scores for each target picking method (five) run on each of the production survey datasets gave 25 scores. The WAA airborne data was compared to the manual picks and produced four sets of scores. Finally, the WAA transect data consisted of only three sets of scores because the MF algorithm was not applied and the other automatic methods were compared to the manual picks. Performance results for the different datasets are summarized in Table 8. All the production survey datasets compared the declarations made by the different methods to the available ground truth to calculate the Pd [8]. All the WAA survey datasets compared the declarations made by the automatic pickers to the picks made by the commercial expert to calculate the Pd and Pfa because ground truth did not exist. The maximum Pd is 1, but the maximum Pfa could be greater than 1 because it is based on the number of manual picks. The ground truth for APG is well documented. For this reason the rBAR and characterization target parameter accuracy (location, depth, and size) were also calculated for the APG dataset. Because only a select number of targets has been released to the

public, the scoring for the APG dataset was done by analysts from the Institute for Defense Analyses.

Table 8. Performance Criteria for This Demonstration.

Performance Criterion	Expected Performance (metric)	Performance Confirmation Method	Actual Performance
Ease of use	Limited training required for users experienced in Oasis montaj™	General observations	Some training required to set proper parameters for data processor experienced in Oasis montaj™
Robustness	Analysis not hindered by bugs or deficiencies.	General observations	Analysis flow not seriously interrupted by bugs
Pd-production surveys (ground truth)	>0.9	Comparison to ground truth data	0.15–0.99
Pd-WAA surveys (manual picks)	>0.8	Comparison to manual picks	0.490–0.76
rBAR (APG only)	NA	Comparison to ground truth data	0.105–0.615
Pfa-WAA surveys (manual picks)	<0.25	Comparison to manual picks	0.02–0.90
Setup time	<4 hours	Setup time logged manually	0.1–5.45 hours
Processing time	<0.25 hr.	Processing time logged manually	.02–.25
Detection location accuracy	90% <0.5 m	Comparison to ground truth data and manual picks	63–95%
Characterization size accuracy (APG only)	90% <0.3 m	Comparison to ground truth data	39–44%
Characterization location accuracy (APG only)	90% <0.3 m	Comparison to ground truth data	90–93%
Characterization depth accuracy (APG only)	90 % <0.3 m	Comparison to ground truth data	94–97%

4.3 DATA ASSESSMENT

The first phase of the demonstration used the 60-dipole synthetic dataset to explore the parameter space and optimize the algorithms for the four target pickers. We varied their different parameters to evaluate and document their effect and to determine if certain "rules of thumb" could be developed. This information was used to guide us when applying the target pickers to the datasets in the demonstration. In addition to this knowledge, Phase 1 was also used to select a set of starting parameters for each automatic picker that was used in Phase 2.

Phase 2 applied the target pickers to the seven magnetic datasets using the default parameters output from Phase 1. Because each dataset had its own unique data characteristics, the starting parameters needed to be adjusted to achieve the best performance. Of the automatic methods, the AS and wavelet method gave the best results overall, but each method had its own strengths and weaknesses and the best method to use was very data-dependent. A general observation for all the automatic pickers is that they should not be run blindly. The analyst should carefully choose their parameters and analyze the results. The process of iteratively changing parameters

and visual review of the results was essential in selecting the best parameters and producing the best results.

The AS method was the fastest and simplest method. It worked well on a range of target sizes and densities. Its main weakness was picking targets in areas with a variety of background geology or noise levels because a hard threshold is required.

The wavelet method worked well on a range of target sizes and densities. It performed better than the other methods at picking targets that were clustered. Its main weaknesses were the complexity of the parameters and over picking in areas with geology, noise, or poor data quality.

The clustering method performed well detecting isolated targets with similar sizes. The clustering algorithm had problems picking anomalies in areas with high geology, noise, or a range of target sizes. There were also multiple parameters that needed to be set.

The MF method was hindered by its requirement to have total data coverage within the filter box. This would increase geophysical data collection costs because additional data would need to be collected around the perimeter of the survey area. It had difficulty with overlapping targets, range of target sizes, and poor data quality. The one area it excelled at was picking targets in areas with a variety of geology.

Overall, the manual method proved to be the best at picking valid targets, especially in areas with varying amounts of geology and background noise. In general, the manual picker was able to set a lower threshold for each dataset than the automatic methods because he can screen out anomalies caused by noisy data or geology and pick the small amplitude anomalies located in the quieter areas. The main drawbacks to the manual method are time, operator bias, and operator error. In this demonstration the manual method was four to 50 times slower (not including setup time) than the automatic methods, depending on the dataset.

5.0 COST ASSESSMENT

5.1 COST REPORTING

This demonstration focuses on detecting anomalies observed in magnetic data. As such, it encompasses only a small subset of costs that are typically associated with full-scale demonstrations. The relevant cost categories and actual costs for this demonstration are shown in Table 9.

Table 9. Demonstration Cost Categories and Details.

Cost Category	Details	Subcategory	Time (hours)	Costs* ($)
Data analysis	Setup parameters for identifying anomalies	Analytic signal	1.5	150
		Wavelet	8.2	820
		Clustering	23.7	2,370
		Matched filter**	21.9	2,190
		Manual	0	0
Data analysis	Running automatic target pickers	Analytic signal	1.7	170
		Wavelet	5.4	540
		Clustering	3.8	380
		Matched filter**	6.2	620
		Manual	43	4,300

*Cost assume a fully-loaded labor rate of $100 per hour.
** Matched filter hours include only six of the seven datasets because it could not be run on the WAA Pueblo transect data.

This demonstration analyzed seven data sets consisting of roughly 7 hectares of production survey data and 82 hectares of WAA data. Approximately 3,000 anomalies were identified with each picking method. The estimated costs required to analyze the datasets with each of the picking methods, excluding one-time, demonstration-related costs such as experimentation, optimization, non-routine analysis and testing, and reporting are presented in Table 10. The costs associated with setting up the parameters in Table 10 assume only one setup and not the 7 setups required under this demonstration. The estimated cost was calculated by taking the average setup cost. These costs will be more indicative of a real-world implementation because it is likely only one setup will be required. Also, the table includes costs for using all methods to detect anomalies. In the real world, only one of the automatic methods would be used to select anomalies; therefore, the real-world costs for each method were calculated and summarized in the bottom section of the table.

Table 10. Data Analysis Cost Categories and Details.

Cost Category	Details	Subcategory	Time (hours)	Costs* ($)
Data Analysis	Setting up parameters for different methods	Analytic signal	.2	20
		Wavelet	1.2	120
		Clustering	3.4	340
		Matched filter	3.2	320
		Manual	0	0
Data Analysis	Picking targets using the different methods	Analytic signal	1.7	170
		Wavelet	5.4	540
		Clustering	3.8	380
		Matched filter**	6.2	620
		Manual	43	4,300
Subtotal	**Total for each method**	**Analytic signal**	**1.9**	**190**
		Wavelet	**6.6**	**660**
		Clustering	**7.2**	**720**
		Matched filter**	**9.4**	**940**
		Manual	**43**	**4,300**

*Costs assume a fully-loaded labor rate of $100 per hour.
** Matched filter hours include only six of the seven datasets because it could not be run on the WAA Pueblo transect data.

5.2 COST ANALYSIS

The baseline alternative to the automatic target pickers is manual target selection. Implementing the automatic picking methods used in this demonstration should considerably reduce the time and thus cost required to pick anomalies when compared to the manual method. The amount of cost savings will depend on the data, which will determine the most efficient automatic method. In areas with isolated anomalies and low background noise or geology, the cost savings will be maximized because the automatic pickers are able to detect over 90% of the anomalies in a fraction of the time compared to the manual method. For this best case scenario, we will assume a detection rate of 95% using the AS method. The setup time for the AS method is minimal for the average dataset, and it runs the quickest of the automatic methods evaluated in this demonstration. Using this demonstration as a guide, the AS method would cost approximately $200 compared to $4,300 for the manual method. If the manual method is used to select the final 5% of the targets and we assume the additional costs will be equivalent to 15% of the total costs for the manual method, the cost savings will be about 80% compared to using only the manual method.

As the geologic noise increases or data quality decreases, the cost savings will diminish but still should be significant. Even the toughest datasets in this demonstration will produce cost savings. For example, the airborne WAA dataset at Pueblo contained an abundance of geology that resulted in Pds of around 0.5 for the automatic pickers. The AS required less than an hour to setup and run while the manual method took 9 hours. Even if it takes an additional 5 hours of manual picking to select the other half of the targets, the time savings will be 3 hours or 33%. The cost savings may appear to be significantly reduced if different methods such as the MF or clustering algorithm are used because of the increased time to setup the final parameters or the longer processing time. But the processing time is mainly a function of the computer run time, and the data analyst is able to do other tasks while the algorithms are running. Large datasets

that will take a long time to complete can be run in batch mode at off hours, whereas the manual method is entirely hands-on and labor-intensive.

The parameter setup time represented a large portion of the processing time for the relatively small datasets used in this demonstration. The ground-based surveys ranged from 0.3 to 10 acres in size. On the other hand, large-scale cleanup efforts are typically hundreds of acres so the setup costs will be a trivial portion of the total costs. Assuming the geology, data quality, and data objectives for the survey area are relatively constant, the automatic target picking parameters should need minimal changes. If we compare only the time to actually run the automatic methods to the manual method, we find the processing time of the automatic pickers is roughly 10% of the time for the manual method. The actual cost savings is greater assuming the data analyst is attending to other tasks while the automatic methods are processing. If we factor in 10-40% additional time to fill in missing anomalies using the manual method, there is still a cost savings of 50-80% achieved by using the automatic picking methods.

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6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The target picking methods demonstrated here are dependent on data quality, target size, geology, SNR, and target density. Magnetic data that possess a high SNR and accurate spatial positions will produce higher Pds and potentially fewer false alarms. Although high quality data is desired, some of the automatic picking methods performed well in this demonstration using data with fiducial-based positions.

The site-specific factors that will have a large impact on the potential cost savings are the range of target sizes, target density, and geology. As mentioned in this report, many of the automatic target picking algorithms required a threshold parameter to be set. This causes a major problem in areas with varying amounts of geology and background noise. Setting the threshold at a level to detect the smallest targets produces many false positives due to geology, whereas many targets will be missed if the threshold is set above the background geology. An increase in anomalies that need manual intervention will decrease the potential cost savings realized by using the automatic methods.

The analysis costs may be marginally reduced as the learning curve on the picking methods increases. The experienced data analyst will be able to determine more quickly which method to use for a given dataset. The experienced analyst will also be able to set up the optimum parameters in less time and be able to ascertain if they need to be altered due to changing site conditions. For large-scale surveys, these setup costs are minimal in comparison to the entire target picking process. The picking method that is ideal for a site should not significantly alter the total cost because the difference in setup time is a one-time expense, and the additional processing time for different methods affects only the computer run time and not analysts' labor.

6.2 PERFORMANCE OBSERVATIONS

The primary performance criteria in this demonstration are Pd, Pfa, location accuracy, and target picking time. In other words, the automatic methods should detect a high percentage of targets with minimal false alarms in a small amount of time compared to the manual method. Many of the factors (target density, target size, geology) that determine the ultimate success of the automatic pickers are not under our direct control. The main reason that some automatic pickers did not reach the performance goals was related to signal-to-noise problems. In most cases, there was too much noise caused by geology in the area to achieve a high Pd without a high Pfa so the Pd was sacrificed to limit the Pfa. Even in these situations, cost savings will be achieved compared to using only the manual method.

6.3 SCALE-UP

There are no critical issues with regard to scaling up the demonstration costs reported here to larger, full-scale implementations. Although the algorithms are able to process large amounts of data, their computational efficiency is dependent on the amount of RAM available. This should not be a problem because most target picking on large-scale surveys are typically done on a smaller grid-by-grid basis that is easily supported by a computer with standard specifications.

6.4 OTHER SIGNIFICANT OBSERVATIONS

There are no critical issues with regard to the implementation of the automatic target picking methods. All methods are currently operational under the Oasis montaj software platform that is used by a large percentage of the UXO community. The target picking algorithms would ideally be transitioned to the user community through Geosoft as part of their proposed UXO System.

6.5 LESSONS LEARNED

Of the automatic methods, the AS and wavelet method gave the best results overall, but each of the methods had their own strengths and weaknesses, and the best method to use was very data-dependent. A general observation for all the automatic pickers is that they should not be run blindly. The analyst should choose parameters carefully and analyze the results. The process of iteratively changing parameters and visual review of the results was essential in selecting the best parameters.

The best use of the automatic target pickers may be to quickly and consistently select all the strong isolated targets by setting the picking parameters to minimize false alarms. The remaining anomalies can then be selected using the manual method. This combines the strengths of each method and will result in a better product compared to using only the automatic methods and will save costs compared to using only the manual method.

6.6 END USER ISSUES

The end users of this data analysis technology include private contractors who conduct geophysical investigations in support of UXO cleanup programs and government employees who provide technical oversight. This demonstration will introduce the stakeholders and end users to the applicability of different automatic target pickers to their data. This basic information will help improve the results and cost savings of future geophysical investigations conducted by others.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

At a given site, the methods and techniques for a proposed geophysical survey to detect buried munitions needs to be tested and evaluated. As part of this process, a geophysical prove-out is constructed and used to identify the capabilities of the proposed technologies. At this time, the results and parameters of the different automatic picking methods can be evaluated. A dig sheet identifying potential targets in the geophysical prove-out as well as a description of the technology and optimum parameters selected is submitted to the Corps of Engineers for review and approval.

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APPENDIX A

POINTS OF CONTACT

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